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# Mechatronic Aeropendulum: Demonstration of Linear and Nonlinear Feedback Control Principles With MATLAB/Simulink Real-Time Windows Target

Eniko T. Enikov, *Member, IEEE*, and Giampiero Campa, *Member, IEEE*

**Abstract**—This paper presents a low-cost hands-on experiment for a classical undergraduate controls course for non-electrical engineering majors. The setup consists of a small dc electrical motor attached to one of the ends of a light rod. The motor drives a 2-in propeller and allows the rod to swing. Angular position is measured by a potentiometer attached to the pivot point. A custom-designed circuit board produces the controlled voltage input to the motor. The target board is powered and communicates with the PC through its USB port using a virtual RS-232 port. A simple MATLAB/Simulink module has been created to read the pendulum angle and send a command signal to the motor. The module is based on Real-time Windows Target software, which allows a sampling rate of up to 200 Hz. Students are able to design and test classical PID and phase lead-lag controllers, as well as modern controllers, including state-space controller design combined with feedback linearization. A semester-long series of assignments is described that can be carried out without the need for a specialized laboratory or teaching assistants. The project was tested in a classical control systems design class of senior-level mechanical engineering students. Student feedback and survey data on the effectiveness of the modules are also presented.

**Index Terms**—Feedback linearization, linear feedback control, real-time control, real-time windows target, Simulink.

## I. INTRODUCTION

**H**ANDS-ON laboratories have always been an integral part of the engineering curriculum. Their importance has been recognized by the Accreditation Board of Engineering Technology (ABET) and its predecessors by creating criteria requiring adequate laboratory practice for students [1]–[4]. During the last three decades, engineering laboratories have become more complex, including simulation tools and computer-controlled test and measurement equipment [5], [6]. This increased sophistication has also led to more expensive equipment [7], [8]. The inclusion of such laboratory courses in the undergraduate curriculum is challenging, due to the large numbers of students and the increased demands for instruction

and equipment time. Hands-on experience, on the other hand, is invaluable for active and sensory learning styles, which are the predominant types of learning styles exhibited by undergraduate students [9]–[12]. This paper describes the development and testing of a new low-cost portable laboratory module, designed to supplement the experience of students taking their first course in controls system design.

While there are many turn-key desktop systems designed to illustrate controls systems courses, portable kits (such as Arduino) are primarily designed for mechatronics and embedded computing courses [13], [14]. As such, they require programming environments, installation of additional software, and additional plug-in modules for operating dc motors and other actuators. Furthermore, unless advanced circuit boards and processors are used, implementing a PID or other dynamic compensators is cumbersome and requires training in digital control and programming. With the emergence of the MATLAB Simulink graphical programming environment, modeling and simulation of various plants and controllers can be accomplished quite easily by students who might not have extensive training in digital control and numerical methods. However, practical implementation of such controllers remains illusive for most undergraduate students outside of electrical and mechatronics engineering programs. Therefore, the objective of this project was to develop a simple physical plant that can be used seamlessly with the Simulink Real-Time Windows Target environment to allow students who are not in Electrical Engineering programs to implement and test real-time controllers using drag-and-drop-style graphical programming.

In the Department of Aerospace and Mechanical Engineering of The University of Arizona, Tucson, it is not unusual for the Control System Design course to have enrollments of over 100 students. This makes offering a laboratory section within the course nearly impossible. The experiment described here was developed primarily as a way to provide some practical experience for students, using an inexpensive and portable setup that can be taken home. The experiment was developed following the principles of the variational theory of learning developed by Marton and coworkers [15], [16] and the approach of guided discovery/interactive-engagement labs characteristic of several well-known labs, such as the Modeling Workshop Project [17], Socratic Dialogue Inducing Labs [18], Real Time Physics [19], and Tools for Scientific Thinking [20]. The portability and low cost of the setup allowed the students to conduct experiments during the entire semester and use the device to complete a term project. In addition to significantly reducing the cost of offering

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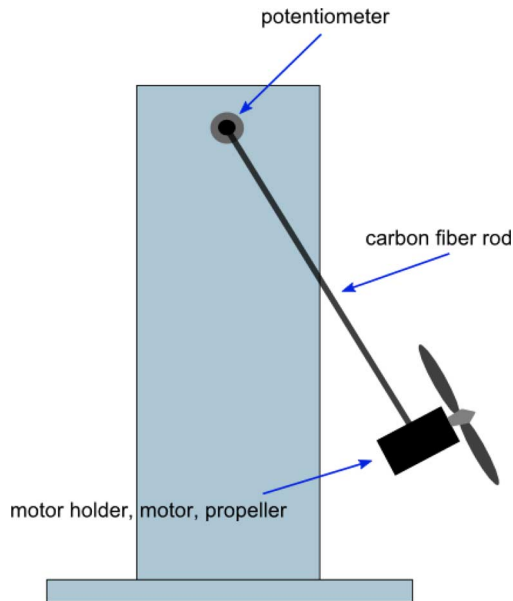


Fig. 1. Aeropendulum: dc-motor/propeller-driven pendulum.



Fig. 2. Target board.

an experimental component, the experimental module provided an opportunity to demonstrate concepts from system identification, nonlinear feedback control, and digital control.

## II. HARDWARE DESCRIPTION

### A. Aeropendulum

The setup consists of a small dc electric motor driven by a 5-V pulse-width modulated (PWM) signal. The motor is attached to the free end of a light carbon rod, while the other end of the rod is connected to the shaft of a low-friction potentiometer. The potentiometer is fixed on a plastic stand at a height where the pendulum can swing freely (see Fig. 1). A 2-in propeller (model U-80) is attached to the motor shaft to produce a thrust force in order to control the angular position of the pendulum. A self-calibrating step during the initialization allows the system to automatically find the vertical position (origin of the coordinate system).

### B. Target Board

A custom-designed circuit board produces the controlled voltage supply for the motor via PWM with a resolution of 0.05 V (see Fig. 2). It also reads the voltage on the potentiometer, which is proportional to the angular position of the



Fig. 3. Adjustable pendulum with counterweight.

pendulum. These functions are implemented using a Freescale MC9S08JM16 microcontroller. The apparatus communicates with the controlling computer (PC, Mac, or Linux) using the USB protocol, eliminating the need for an increasingly rare serial port. The device is powered by two USB ports that are capable of pulling a total of 600 mA from the host computer. The microcontroller is commanded to apply various PWM signals to appropriate sides of the H-bridge IC drives (two P-MOS, two N-MOS, ZETEX ZXMHC10A07T8TA), depending on the desired direction. When queried, the microprocessor returns the average of several 12-bit analog-to-digital conversions to MATLAB, which is then correlated through a proportionality constant to the angle of the pendulum.

In its latest implementation, the aeropendulum kit has been modified to include a movable counterweight and variable length rod, as shown in Fig. 3. This simple modification allows the instructor to adjust the inertia of the pendulum, as well as the required feedback linearization action, and thus produce an individualized setup for each student.

### C. Simulink Environment

The experiment also illustrates the use of the MATLAB/Simulink Real-Time Windows Target (RTW) environment (see Fig. 4). The RTW module performs classical control experiments using hardware-in-the-loop simulations. Using RTW, the sampling time was reduced by an order of magnitude to 5 ms. This was achieved by a built-in functionality of RTW that compiles the Simulink model down to C or C++ code, and then builds a native executable file. Removing the need for an interpreter greatly improves the efficiency of the simulation. Packet-In and Packet-Out blocks are used in the RTW model to communicate with the microcontroller. The Packet-Out



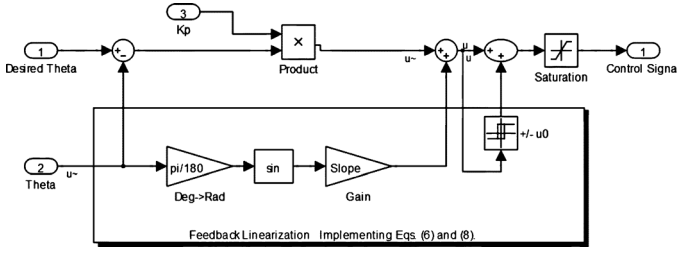


Fig. 7. Implementation of feedback linearization according to (6) and (8).

Coefficients  $K_+$  and  $K_-$  correspond to positive and negative input voltages and are different due to the asymmetry of the propeller operation. Using this model and experimenting with positive and negative inputs, the students determine approximate values of these coefficients extracted from a bidirectional version of the plot in Fig. 6

$$\frac{K}{mg} = \frac{K_+}{mg} = \frac{2K_-}{mg} = \frac{1}{145}$$

where the factor 2 reflects the experimentally observed fact that the propeller is twice as efficient in the forward direction as in the reverse direction ( $K_+ = 2K_-$ ). The next step is to eliminate the observed dead-band. To this end, the students are instructed to use a discontinuous control law

$$u = \begin{cases} \bar{u} + u_0, & \text{if } \bar{u} > 0 \\ \bar{u} - u_0, & \text{if } \bar{u} < 0 \end{cases} \quad (6)$$

which has the effect of canceling the dead-band region. As is evident from Fig. 6, the approximate value of  $u_0$  is 22. The resulting model in terms of the new input variable  $\bar{u}$  is

$$mL^2\ddot{\theta} = -mgL \sin \theta - c\dot{\theta} + K L \bar{u}. \quad (7)$$

Finally, the feedback linearization is achieved through the use of a nonlinear feedback in the form

$$\bar{u} = \frac{mg}{K} \sin \theta + w \quad (8)$$

which cancels out the nonlinear term. The resulting linear system has a simple transfer function with two real poles at 0 and  $-c/mL^2$ , respectively

$$\frac{\Theta(s)}{W(s)} = \frac{KL}{mL^2s^2 + cs}. \quad (9)$$

Implementation of the nonlinear feedback linearization represented by (6) and (8) is shown in Fig. 7. Since the propeller is more efficient in the forward direction, only positive command signals are considered, and elimination of the dead zone is reduced to addition of the offset  $u_0$ . The cancellation of the effect of gravity is accomplished by the addition of  $mg \sin \theta$ . The resulting linearized system is a classical one (presented in all textbooks on controls) and is easy to relate to the associated lectures.

The final step in developing the plant model is to identify the parameters of (9). Due to the integrator term (pole at zero), the system is of type 1 and will produce an unbounded response if tested with a step input. Another interesting observation students make is that when  $\bar{u} = 0$ , the pendulum is “weightless”

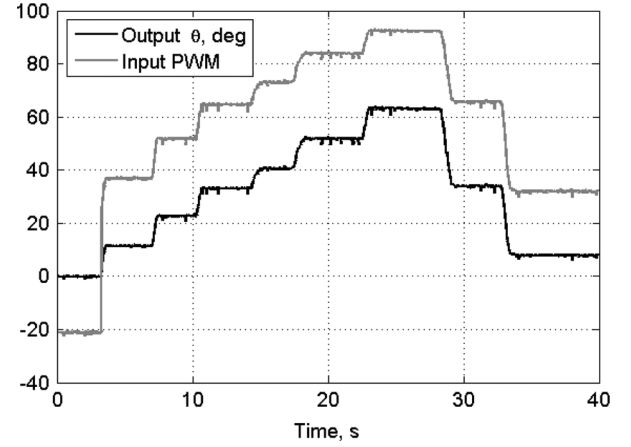


Fig. 8. Feedback-linearized pendulum (“weightless”) response.

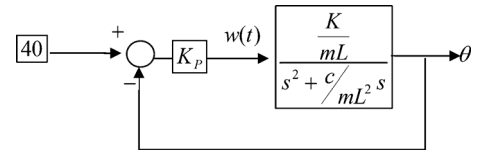


Fig. 9. Closed-loop system.

due to feedback linearization. It is easy to show that under such conditions  $\theta = \text{const}$  is a solution to (9). Therefore, if the pendulum is manually pushed to a particular angle, it remains there due to the automatic adjustment of power according to (8). Fig. 8 demonstrates the corresponding response. If the feedback linearization is not perfect due to errors in the parameter estimation, the pendulum will have the tendency to droop or rise, which is easy to observe visually.

### C. System Identification of Linearized Plant

As a third assignment, the students are asked to identify the system type of the linearized plant (9). Generally, steady-state errors and associated system types are covered early in the semester, therefore this step tends to serve as a reminder and illustration of a known material. Typically, students recognize the type-1 behavior and correctly expect to see a zero or negligible steady-state error. The suggested approach is to implement a unit-feedback control of (9) by setting

$$w = K_p(\theta_0 - \theta) \quad (10)$$

with  $K_p = 1$ . The resulting block diagram is shown in Fig. 9. Students then use the step response of this system to identify the values of the parameters  $K/mL$  and  $c/mL^2$  by deriving the following formulas relating the natural frequency  $\omega_n$  and damping  $\zeta$  of a second-order system to the physical parameters of the model:

$$\begin{aligned} \omega_n^2 &= \frac{K}{mL} \\ 2\zeta\omega_n &= \frac{c}{mL^2}. \end{aligned} \quad (11)$$

A sample experimental plot of the step response for a command input of 40 degrees is shown in Fig. 10. Through this experiment, the students are able to apply the classical formulas

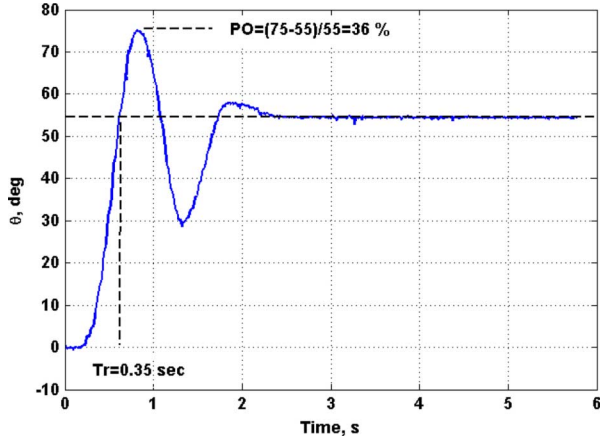


Fig. 10. Step response of closed-loop system.

presented in the course lectures to relate the plant parameters to system response parameters such as overshoot and rise-time

$$P.O. = \exp(-\zeta\pi/\sqrt{1-\zeta^2}) = 0.36$$

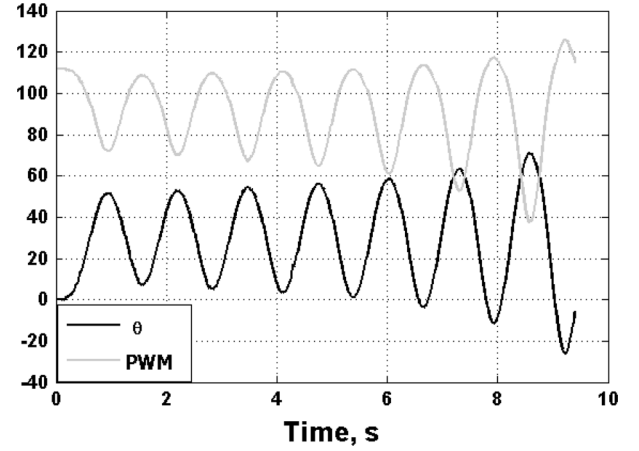
$$t_{\text{rise}} = \frac{1.8}{\omega_n} = 0.35. \quad (12)$$

In a more recent implementation, the length of the rod of the pendulum can be adjusted. When working with shorter lengths, the inertia is reduced, and the friction in the potentiometer becomes more dominant. The unit-feedback response of such pendulums has no overshoot. In such cases, students can use higher values of the feedback gain, e.g.,  $K_p = 2$ , leading to an underdamped response, and follow the same identification method. Alternatively, MATLAB's System Identification Toolbox `pem` command can be used to automatically estimate the parameters of the system. An example of its use is available online [21].

#### D. Model Fidelity

With the parameters fully identified, it is now possible to examine the validity of the model. To this end, the students are asked to apply the root locus design method and determine the behavior of the system (9)–(10) under different values of the feedback gain  $K_p$ . Using the root locus method, students predict that the system is stable under all values of  $K_p$ . However, when asked to run experiments for  $K_p = 1, 2, 2.5, 3$ , they realize that the response is stable for low values of the gain, and that the system loses its stability and the pendulum undergoes unstable oscillations, beyond a certain critical gain, as shown in Fig. 11. This experience leads to the fourth task, where the students are asked to examine their model and propose possible reasons for the observed discrepancy. Interestingly, the majority of the students (over 66%) provide inaccurate or superficial answers (discussed in Section IV). Upon submission of their responses, students are provided with a guided solution directing them to refine the model of the motor/propeller model by incorporating the dynamics of the motor current and propeller rotation. This results in the addition of a voltage-current equation

$$V = Ri + K_v\omega + L_{\text{ind}}\frac{di}{dt} \quad (13)$$

Fig. 11. Unstable response for  $K_p = 3$ .

where  $R$  is the resistance of the motor coils,  $K_v$  is the back emf constant, and  $L_{\text{ind}}$  is the inductance of the motor coil. Similarly, the rotor dynamics is governed by

$$J_m\dot{\omega} = K_t i - C_Q \frac{\rho}{4\pi^2} D^5 \omega^2 \quad (14)$$

where  $K_T$  is the motor torque constant,  $C_Q$  is the aerodynamic torque (drag) coefficient,  $\rho$  is the air density, and  $D$  is the diameter of the propeller [22]. Solving (14) for  $i$  and substituting in (13), it is easy to see that  $V$  and  $\omega$  are related through a second-order nonlinear differential equation for  $\omega$ . Consequently, the input signal  $\tilde{u}$  and the thrust force of the propeller are also subject to the dynamics of the associated poles. With this explanation, students are able to examine the effect of these two additional poles by assuming that they are approximately equal (critically damped pole pair) and reexamine the root locus of a fourth-order system

$$\frac{\Theta(s)}{W(s)} = \frac{KL}{mL^2s^2 + cs} \cdot \frac{1}{(1 + T_{D1}s)(1 + T_{D2}s)}. \quad (15)$$

A quick estimate of the effect of these poles can be made by assuming that they are close to each other and by examining a system with a critically damped pole-pair

$$\frac{\Theta(s)}{W(s)} = \frac{5.327}{s^2 + 3.649s} \cdot \frac{1}{(1 + T_Ds)^2} \quad (16)$$

where the actual parameters of the transfer function (9) have been used.

The students are then asked to vary the value of the time constant  $T_D$  until the critical gain predicted from the root-locus agrees with the value obtained from experimentation ( $K_p \approx 3$ ). The corresponding plot is shown in Fig. 12. The resulting time constant is  $T_D \approx 180$  ms, which matches tachometer measurements of the propeller [22]. This experience was well received, in particular by students who had struggled to come up with an explanation for the shortcomings of the second-order model. It also illustrates the use of the variational theory of learning in the design of the experiment. According to this theory, we learn through the experience of difference, rather than recognizing similarities. As Marton and coworkers state [16]: “What we believe is that variation enables learners to experience the



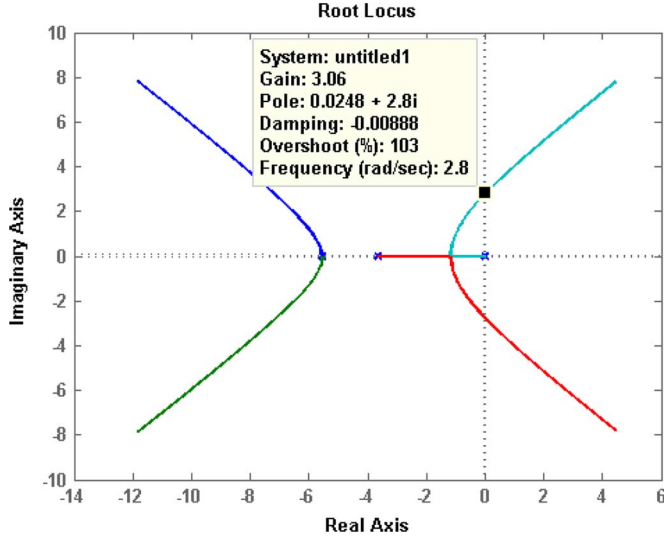


Fig. 12. Root locus of a fourth-order model incorporating motor-propeller dynamics.

features that are critical for a particular learning as well as for the development of certain capabilities. In other words, these features must be experienced as dimensions of variations.”

#### E. Design of Dynamic Compensator

The final assignment associated with the pendulum is to design a dynamic compensator. Typical performance specifications include a steady-state error of not more than 0.5 degrees and a setting time of not more than 3 s. Students are given the freedom of choosing a design method and compensator type, however most prefer using the frequency response techniques (Bode plots). It is worth noting that when the System Identification Toolbox’s pem command is used, the extracted characteristic polynomial usually contains a small nonzero constant term (0.0033 in this case), which reflects the quality of the feedback linearization

$$\frac{\Theta(s)}{W(s)} = \frac{5.327}{s^2 + 3.649s + 0.0033}. \quad (17)$$

Following classroom examples, they import the plant’s transfer function in MATLAB’s SISOTool and use its Bode plot to examine gain crossover frequency and stability margins. The SISOTool allows them to graphically place the poles and zeros of their compensator and adjust the gain. An example of a phase lag (proportional + integral) compensator with a transfer function

$$C_{\text{lag}} = \frac{0.82575(s + 0.4771)}{s + 0.05936} \quad (18)$$

is shown in Fig. 13. Since a Real-Time Windows Target operates in the discrete domain, testing the performance of the compensator (18) requires a conversion of the compensator to a digital (discrete) transfer function using MATLAB’s  $c2d()$  function. The sampling time of the target board is determined by a function generator block inside the Simulink model. Since the target board uses a USB-to-serial driver, the actual data transfer speed and hence the limit of the sampling rate is that

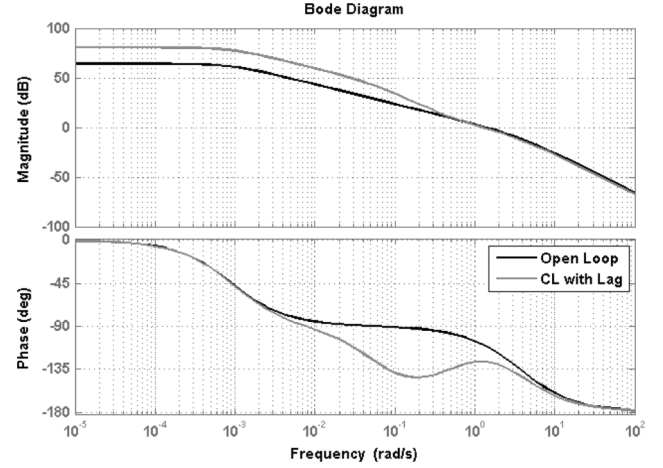


Fig. 13. Design of dynamic compensator (lag) in SISOTool.

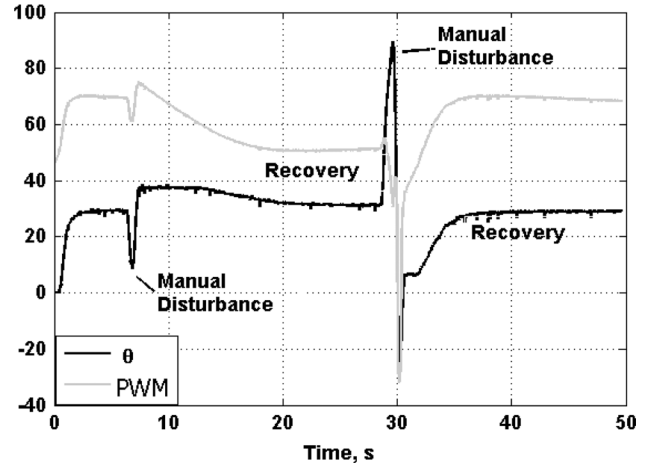


Fig. 14. Step response and disturbance rejection using phase lag compensation.

of the USB. Given the slow speed of the apparatus, we utilize a 10-ms update rate. The corresponding conversion command is  $C_{\text{lagd}} = c2d(C_{\text{lag}}, 0.01, 'zoh')$ , resulting in

$$C_{\text{lagd}} = \frac{0.82575(z - 0.9952)}{z - 0.9994}. \quad (19)$$

Similarly, students perform a phase lead (proportional + derivative) controller design where they place the gain cross-over frequency around 20–30 rad/s. As expected, the resulting response is much faster, but with increased noise and larger overshoot. The response of the dynamically compensated plant with phase lag and lead controllers under multiple manually induced disturbances is shown in Figs. 14 and 15, respectively.

#### IV. EVALUATION

During the 2008–2011 academic years, the project was offered to three cohorts with different instructors. The impact of the project was assessed through student surveys conducted at the end of the course following the protocol approved by the Institutional Review Board. Additional data were drawn from student reports. The data reported here are from a section not taught by any of the authors; instead, the instructional materials and hardware were provided to a different instructor and his

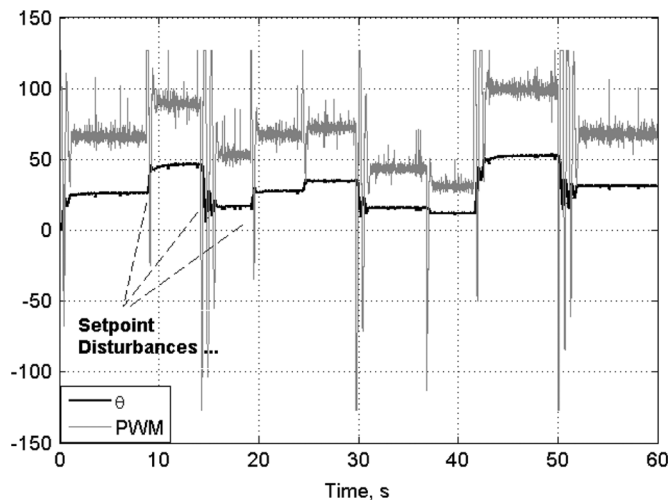


Fig. 15. Step response and disturbance rejection using phase lead compensation.

TABLE I  
STUDENT FEEDBACK ON HOW WELL THE PROJECT ILLUSTRATES TECHNICAL CONCEPTS (PERCENTAGE; NUMBER OF RESPONSES IN PARENTHESES)

To what extent (how well) did the project illustrate the following technical concepts?					Rating Average*
Not at all	Less than expected	More than expected	Very Well		
Relationship between physical system and transfer function					3.21
0.0% (0)	7.1%(2)	64.3%(18)	28.6%(8)		
Second-order system response					3.07
3.6% (1)	10.7%(3)	60.7%(17)	25.0%(7)		
Relationship between stability and gain					3.32
0.0% (0)	10.7%(3)	46.4%(13)	42.9%(12)		
Relationship between overshoot and gain					3.04
3.6% (1)	25.0%(7)	35.7%(10)	35.7%(10)		
Use of root locus					3.07
0.0% (0)	17.9%(5)	57.1%(16)	25.0%(7)		
Use of Bode plots					2.43
14.3% (4)	39.3%(11)	35.7%(10)	10.7%(3)		
System type and steady state error					3.07
7.1% (2)	10.7%(3)	50.0%(14)	32.1%(9)		
Disturbance rejection and system recovery					3.07
7.4% (2)	11.1%(3)	48.1%(13)	33.3%(9)		
Non-linearities and ways to deal with them					3.11
0.0% (0)	14.3%(4)	60.7%(17)	25.0%(7)		
Effects of time delay					3.11
0.0% (0)	17.9%(5)	53.6%(15)	28.6%(8)		

\* Point scale: 1 - Not at all, 2- Less than expected, 3- More than expected, 4- Very well

teaching assistant. However, the results from surveying the authors' sections agree to within 5%–8% in most categories of the data shown here. As part of the evaluation, students were asked questions about the technical content, as well as the implementation and impact of the portable experiment. Table I shows the evaluation of technical content. As expected, the majority of the students found the system quite useful in illustrating the principles of control system design. The highest benefits are derived from better understanding of the relationships between stability

and gain, the importance of transfer functions in capturing the physical models, followed by the ability to deal with nonlinear systems and time delay. Interestingly, the highest gains were achieved in understanding of the relationship of stability and gain. When asked to comment on the discrepancy observed between the theory and experiment, 33% of the students correctly identified the missing rotor dynamics as a possible cause, while 56% felt that the feedback linearization somehow masked the unstable modes or was imperfect, leading to loss of stability. Another 11% looked for physical limitations in the system or faulty components. It appears that the large number of misconceptions, paired with challenging the students' confidence in their ability to model the plant, along with providing a plausible solution to the problem, could explain the highest gains in this category. Further case studies would be required to confirm this observation. Among the least understood topics was the use of Bode plots, perhaps due to the fact that it was covered at the very end of the semester, leaving little time for practice and exploration. The portability and convenience of the implementation of the experiment was evaluated through a second set of questions, where 42.9% of the students reported that they did not need a permanent lab, and another 42.9% had to use a teaching assistant consultation for not more than 1 h. Only 3.6% indicated that more consultation was needed, while 10.7% wanted to have a permanent lab space dedicated to the project. The average duration for completion of the project was 7.78 h.

## V. CONCLUSION

An inexpensive portable experimental setup has been described for use as a hands-on experience for undergraduate students taking senior-level classical control system design courses. The project requires minimal or no supervision without the need for a specialized laboratory space. In 10 out of 11 topics, students self-reported above average learning gains. Highest gains were achieved through a problem that challenges the student's trust and belief in the theory when confronted with an apparent contradiction with experimental observations. Evolution of the project has shown that presenting it as a series of short assignments allows the instructor to provide guidance to the students without sacrificing the ability to encourage individual experimentation. The project is particularly aimed at helping students whose major is not electrical engineering become familiar with the modern developments in implementation of real-time control systems. While simple, the hardware allows demonstration of advanced concepts such as feedback linearization. Evaluation data show that the project is well received by students, and it can be completed independently over an average of 8 h. Parameter variation through modification of the configuration of the pendulum allows the instructor to individualize each kit.

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